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A GENERIC LANDING GEAR DYNAMICS MODEL FOR LASRS++

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Abstract

The Langley Standard Real-time Simulation in C++ (LaSRS++) Generic Gear Model is a simple flexible design that provides realism and can easily simulate different aircraft by changing a few design parameters. Typical closed loop characteristics of the entire aircraft are used to model the dynamics during ground operations. The model consists of three principal functions: struts, braking, and steering. Dynamic characteristics are assumed to produce nearly critical damping with a fixed natural frequency in all axes. The model outputs the body frame axial, lateral, and vertical forces and roll, pitch, and yaw moments generated by the landing gear. This model is used in the simulation of the HL-20 lifting body, general aviation aircraft and a generic fighter similar to an F-16 at NASA Langley Research Center, including motion base operations.

Introduction

The Langley Standard Real-time Simulation in C++ (LaSRS++) is an object-oriented framework used to simulate a variety of aircraft, including general aviation aircraft, fighters, civil transports, and spacecraft. The goal of the LaSRS++ Generic Gear Model is to produce a simple flexible design that appears to operate realistically and can easily simulate different aircraft by changing a few design parameters.

The usual approach for simulating aircraft landing gear is to have detailed component and geometry models that produce open loop dynamics. This level of detail is needed when the objective of the simulation is to evaluate landing gear performance. But sometimes the data for a detailed model is not available and often a simple model that looks correct to a pilot is all that is needed.

In this design typical closed loop characteristics of the entire aircraft dynamics are used to model the contribution of landing gear forces and moments during ground operations. This results in a simple flexible design that appears to operate realistically to a pilot. Changing the design values can easily simulate different aircraft.

The generic landing gear model assumes the aircraft has tricycle landing gear with two main wheels, including brakes, and a steerable nose wheel, as shown in Figure 1. Constant values required by the model are the weight and moments of inertia of the aircraft, the body frame location of the center of gravity and wheel-ground contact points. The body frame used for the Generic Gear Model is defined with the origin at the reference center of gravity (CG), the X-axis forward, the Y-axis to the right, and the Z-axis down toward the floor of the aircraft.

Dynamic inputs to the model include aircraft attitude and rotational rates, the body frame velocity vector of the center of gravity, and body frame forces and moments produced by aerodynamics and propulsion. Pilot inputs include brake pedal inputs for left and right main gear brakes and rudder pedal inputs for nose wheel steering. Dynamic characteristics are assumed to produce nearly critical damping with a fixed natural frequency in all axes. The model outputs body frame axial, lateral, and vertical forces and roll, pitch, and yaw moments generated by the landing gear.

The model consists of three principal functions: struts, braking, and steering. The strut model produces vertical normal forces with square law

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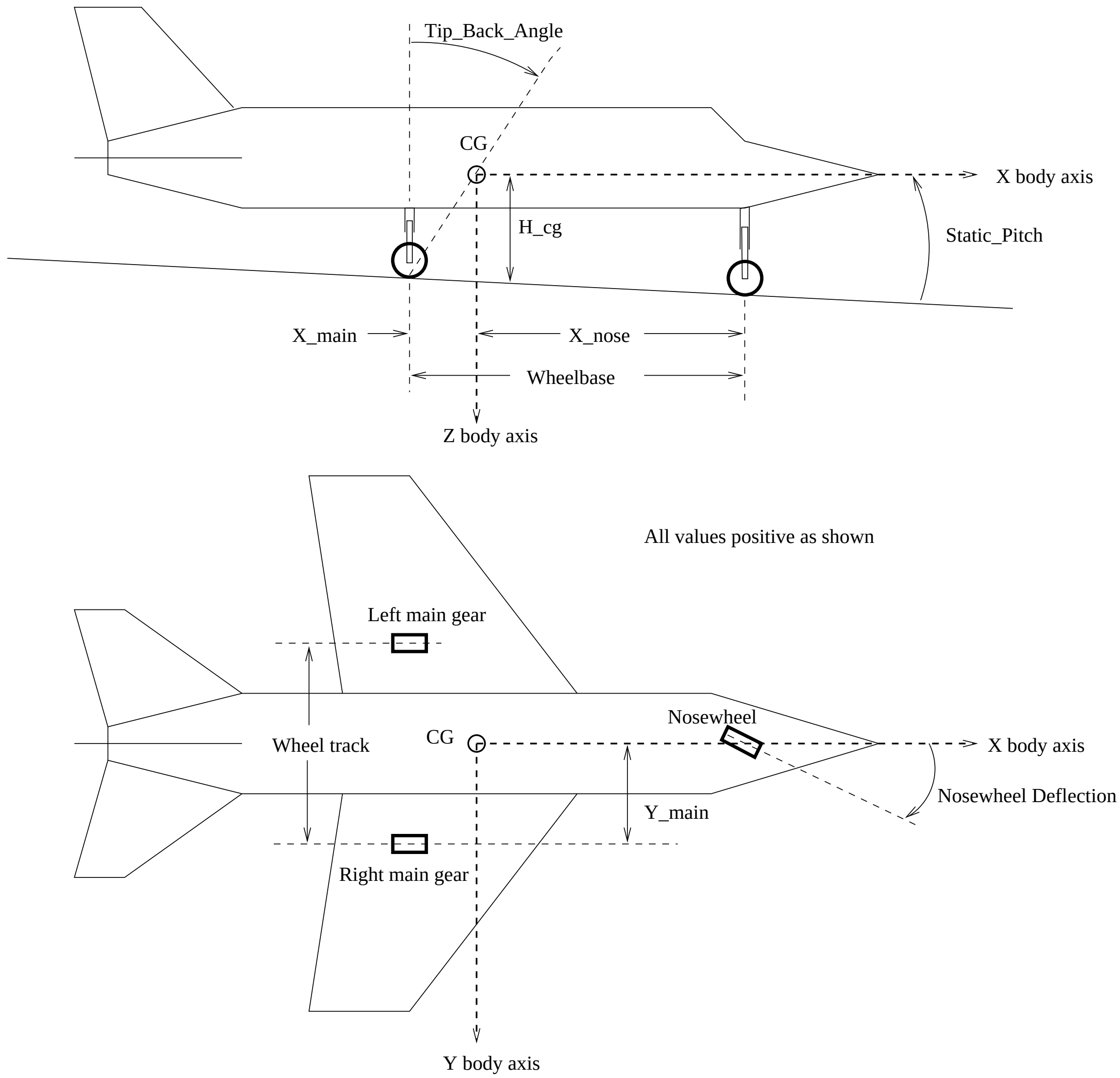

Figure 1. Generic Landing Gear Geometry

damping, including the effects of stroke length limiting impact G's and the touchdown sink rate.

The pitching moment arm of the main gears is based on a linearized relation between the tip back angle and the static attitude of the aircraft. Braking axial forces assume a fixed rolling friction coefficient and a maximum braking coefficient of friction. Gear geometry is used to produce differential braking yaw moments and side forces are limited to simulate skidding. Axial and lateral forces decay as the aircraft stops. Nose wheel steering produces lateral forces and yaw moments based on a simple 'tricycle approximation' that avoids the traditional problem of stopping without dividing by zero.

Model Outputs

The LaSRS++ equations of motion calculate accelerations based on force and moment inputs, regardless of the state of the simulation. The Generic Gear class must generate body frame axial, lateral and vertical forces, and roll, pitch and yaw moments and provide accessor functions for other classes to use them. Output values must be updated at the iteration rate of the simulation, which for LaSRS++ is 32 iterations per second or higher. Note that this design approach precludes stopping the aircraft by forcing zero velocity inside the equations of motion. The Generic Gear Model must generate forces and moments that stop the aircraft and hold it in position when it has stopped. Also the landing gear model must function during reset, trim and hold modes as well as in operate.

Model Constants

To use the Generic Gear Model it is necessary to supply data about the inertia and geometry of the aircraft being simulated. These values are assumed to be constant for a particular aircraft. The aircraft specifications include the landing weight of the aircraft and its roll, pitch, and yaw moments of inertia. The body frame coordinates of the center of gravity and the wheel-ground contact points with the aircraft stopped must be provided. The maximum stroke of the struts or the static pitch angle must also be specified.

The dynamic characteristics are assumed to be the same for all aircraft. The forces produced by the landing gear are generally proportional to the weight of the aircraft. The rolling, cornering, and braking coefficients of friction are independent of the aircraft being simulated. This allows the use of normalized accelerations, thus many of the gains are the same for any aircraft. All aircraft exhibit the same basic rotational characteristics during ground handling--they all have nearly critical damping in all axes and come to rest with wings level at a predictable pitch attitude and altitude of the center of gravity above the ground.

The Generic Gear Model provides default values for all of these model constants. Values can be varied by overloading the constructor function that creates the Generic Gear Model. The values can also be adjusted in real-time by a graphical user interface (GUI) that provides values for mutator functions.

All integrators and filters in LaSRS++ are required to be independent of the iteration rate. The time step is specified in the class constructor.

Variable Inputs

The Generic Gear class calculates the contribution of the landing gear forces and moments to the vehicle equations of motion. However the overall dynamics depend on the total forces and moments, such as those due to gravity, aerodynamics and propulsion. Basically the approach is to determine the total forces and moments that produce the desired dynamics, subtract the effects of gravity, aerodynamics and propulsion, and resolve what is left as the landing gear contribution. Thus the Generic Gear Model is a closed loop approach, fundamentally different from the usual open-loop simulation of ground handling.

To do these calculations the Generic Gear class requires inputs from other classes at the iteration rate of the simulation. The variable quantities that must be input include:

- Roll and pitch attitude and rates
- Yaw (heading) and track angle and rates
- Altitude of the center of gravity above the runway
- Body frame velocity vector
- Body frame forces and moments produced by aerodynamics and propulsion
- Pilot’s brake input for left and right main gears
- Pilot’s pedal input for nose wheel steering angle

Strut Dynamics

The struts produce vertical (or normal) forces that absorb the initial impact of the landing gear on the ground, bring the aircraft to an equilibrium attitude in pitch and roll, and then support the aircraft while rolling, braking, turning and taxiing. When the aircraft completely stops, the struts produce forces and moments that maintain the aircraft wings level with the nose at a predictable pitch attitude and the center of gravity at a predictable height above the surface. All the other forces and moments produced by the landing gear depend on the vertical or normal force produced by the struts.

In flight before landing the strut is extended to its maximum deflection, as shown in Figure 2. The initial ground impact is referred to as touchdown or ‘weight on wheels’. Typically struts generate a force proportional to the square of the sink rate plus a force that depends on the deflection of the strut. This is called ‘square law damping’ and results in a non-linear second order differential equation. As a rule the strut is slightly underdamped--it overshoots the equilibrium deflection and oscillates at least once. The strut is usually designed to absorb a sink rate of about 10 ft/sec by generating an

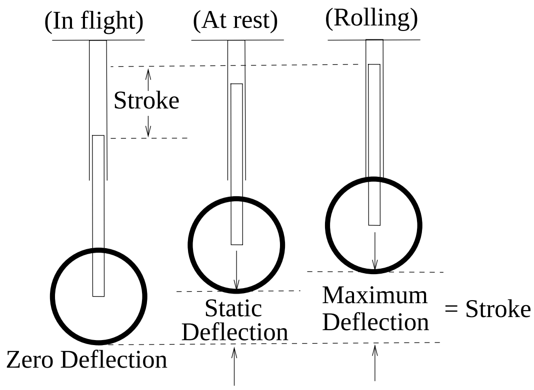

Figure 2. Strut Terminology

upward force that produces about 4 G's ('load-factor') as the strut reaches maximum deflection. More gentle sink rates produce G's proportional to the square of the sink rate. Harder touchdowns would result in crashing a real aircraft. The limit sink rate and load-factor in G's are specified in the Generic Gear constructor constants as described above. According to Raymer [1] the same strut deflection is required for the same sink rate and load-factor on an ultra-light as for an airliner. This is because the normal forces are generally proportional to weight and thus so is acceleration.

When both main gears are on the ground the aircraft rolls to a wings-level attitude very rapidly. The rolling motion is also an underdamped oscillation with small overshoot that damps quickly.

Because the main landing gears are behind the center of gravity they usually produce a nose-down or 'slapdown' pitching moment proportional to the normal force. But the pitch moment arm of the main gear from the center of gravity increases as the aircraft pitches down. The pitch attitude at which the center of gravity is directly above the main gear contact point is called the 'tip back angle'. If the aircraft is pitched higher while rolling forward the landing gear will pitch the nose up instead of down. In the Generic Gear Model a linearized variation of the main gear pitch moment arm depends on the pitch attitude versus the tip back angle.

When the nose gear touches down ('weight on nose gear') its strut also produces a square law underdamped oscillation. This results in the aircraft moving to an equilibrium pitch attitude. The equilibrium pitch attitude will vary depending on braking and aerodynamic pitching moments. The nose gear strut (as the mains) can push the aircraft upwards, but cannot pull it down. When the aircraft stops moving the pitch will assume a constant predictable value.

Braking Dynamics

The wheels produce axial forces due to friction acting on the wheels. The normal force and the coefficient of friction determine the axial forces. The coefficient of friction is the combination of rolling and braking friction, and static friction when the aircraft is stopped. The rolling coefficient of friction is assumed to be constant with a default value of 0.02.

Various references do not agree on the details of how to simulate braking friction. [2,3,4,5] For small brake inputs on a dry runway the coefficient of braking friction is proportional to brake pedal deflection. The maximum braking coefficient depends on the runway condition (dry, wet, or icy) and the speed of the aircraft. Some models make the braking coefficient a function of the 'slip ratio' or ratio of the rotating wheel speed compared to the speed at the non-rotating center of the hub. The braking coefficient is reduced if the wheel stops rotating.

The approach taken in the Generic Gear Model is to make the braking friction coefficient proportional to brake pedal deflection until the maximum value is reached, and then maintain that maximum value, as indicated in Figure 3. This is effectively the same as 'anti-lock' braking. The default value for maximum braking coefficient is 0.6. This can be modified in real-time to simulate wet or icy runways if desired. The variation of maximum braking with forward speed is not simulated because it is unusual to apply maximum braking at very high speeds where it makes a difference.

If the left and right brakes are not equally applied, known as 'differential braking', a yawing moment is generated that is the product of the axial force and the lateral moment arm of the main gear tire. This moment is added to the other yawing moments, including the nose wheel steering moment as described below.

If the main tires are not pointed in the direction they are rolling, a skid angle results. This skid angle produces a side force on the tire tending to

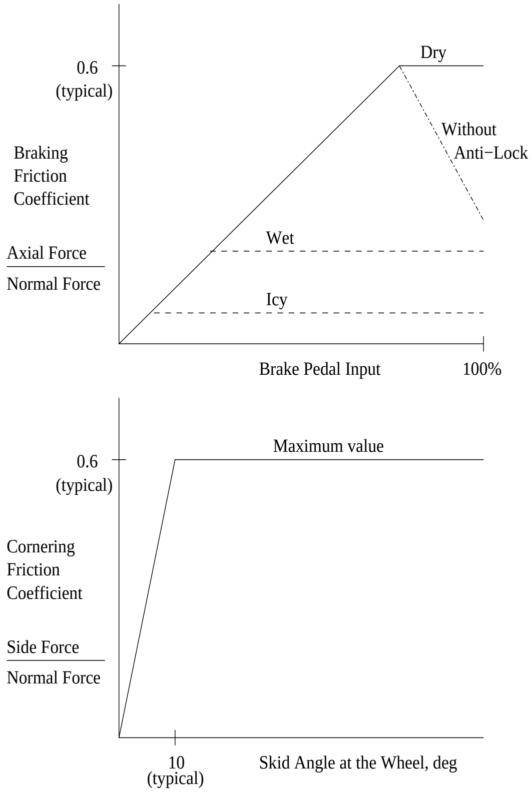

Figure 3. Friction Coefficients

reduce the skid angle. For small skid angles the side force friction coefficient is proportional to the skid angle. But the side force or 'cornering' coefficient is limited depending on the runway condition, the same as for the braking coefficient. The side force is also limited by the amount of braking being applied, partly because the root-sum-square magnitude of the two friction coefficients is physically limited as well.

Probably the most difficult ground dynamics phenomenon to simulate in real-time is stopping the aircraft. When the aircraft stops the friction forces disappear, and the aircraft cannot be moved or turned by using the brakes or nose wheel while it is stopped. If the usual equations are applied continuously the simulated aircraft backs up or turns unrealistically when stopping. Several ground dynamics functions, especially the skid angle, depend on dividing by the speed of the aircraft. If the speed is allowed to go to exactly zero the program will crash due to a 'divide by zero' error. Even if speed only decays to a small number, unrealistic seemingly random results occur.

The classical way to solve this problem is to set the velocity directly to zero inside the equations of motion when the velocity approaches zero. Since the LaSRS++ architecture does not allow the landing gear model to modify the velocity of the aircraft, it can only output forces and moments that are integrated to produce translational and rotational velocities.

In the LaSRS++ Generic Gear Model the axial and lateral friction forces are decayed to zero by making them proportional to forward and lateral velocity at low speeds. This prevents the aircraft from backing up, sliding sideways, or turning after it stops. If there are crosswinds producing aerodynamic side forces, the gear model will produce enough side force to keep the aircraft static, up to the limit of side force friction. Only when the forward thrust of the engines exceeds the static friction will the aircraft start to move again.

Steering Dynamics

The turn rate of the aircraft depends on differential braking, the nose wheel steering angle, and the ground-relative speed of the aircraft. The mathematical relationship between these quantities is the same for all aircraft. Both the main gear and nose gear generate side forces when the tires are not aligned with the direction they are rolling, producing a skid angle. Most ground dynamics models calculate the side forces on all tires depending primarily on the skid angle at the wheel. When the nose wheel is deflected left or right from the fuselage centerline the resulting local skid angle produces a side force and yawing moment that causes the aircraft to turn. The major problem with this open loop approach is that the skid angle becomes very large as the forward velocity decays to zero, causing unrealistic forces and oscillations.

The Generic Gear Model simultaneously solves the problems of nose wheel steering and stopping by using what is called the 'tricycle approximation', as shown in Figure 4. This method resulted from the observation that while turning on the ground the radius of curvature of the turn is always near the intersection of the extended axle lines of the main gear and nose gear. This allows a simple approximation that predicts a reference rate of turn proportional to both the nose wheel steering angle and the

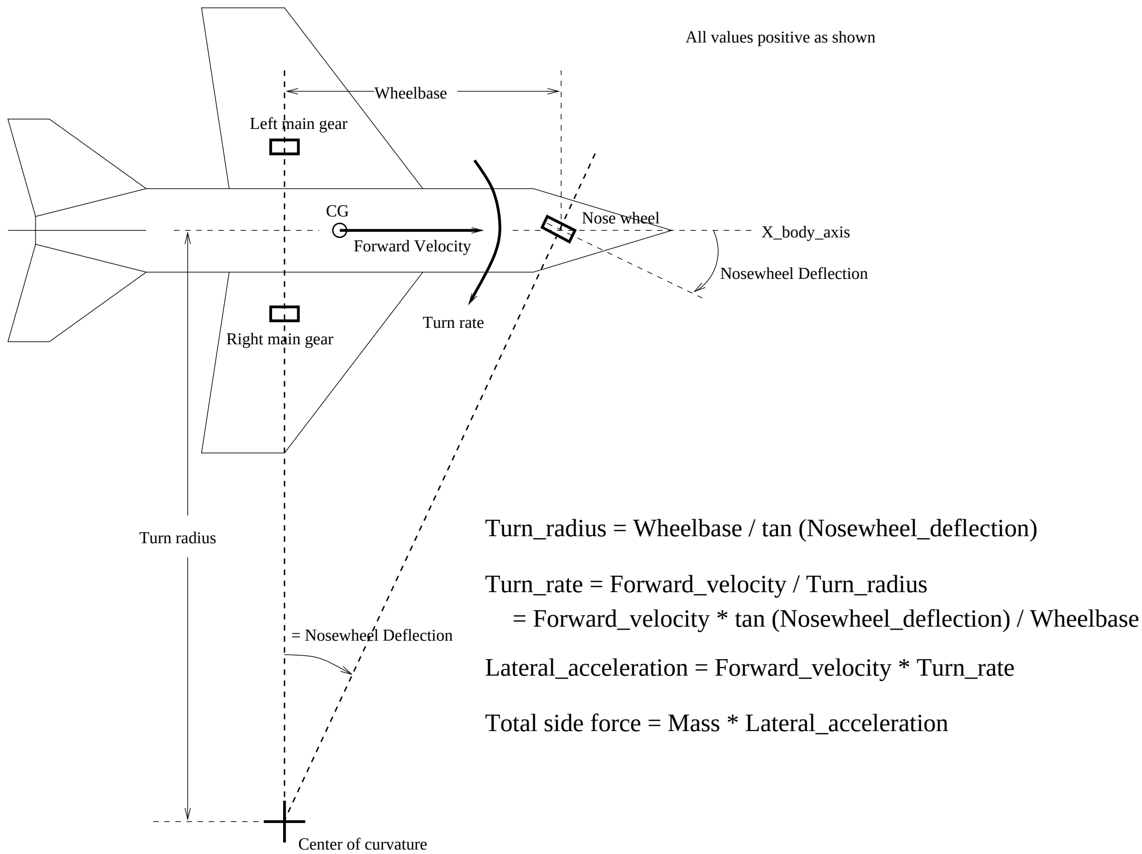

Figure 4. The Tricycle Approximation

forward velocity of the aircraft. The total side or 'centripetal' force to maintain the turn is based on elementary physics. The total yawing moment is proportional to the difference between the reference turn rate and the aircraft yaw rate. The tendency of an unrestrained nose wheel to align with the local velocity vector ('castering') is simulated by adjusting the yaw rate gain. The side force on the nose gear is also limited by the maximum friction coefficient similar to the main wheel model described above.

The Generic Gear Model outputs the required total side force and yawing moment to sustain the turn. Although it is several orders of magnitude simpler, this method produces nearly the same results as the more complex models in the references,[3,5,6] and is smoother at low speeds.

Results

The current version of the real-time update function of the Generic Gear Model that is executed in real-time operate mode consists of a dozen logical decisions and about 30 assignment statements.

The first real-time simulation at Langley to use the LaSRS++ Generic Gear Model was the HL-20 lifting body in August 1999. An earlier version of the model, coded in FORTRAN, was used starting in 1990, because no landing gear model was available for the HL-20. The HL-20 was not primarily concerned with ground dynamics, but pilots were interested in seeing if the vehicle could be stopped in the remaining runway after touchdown. When the simulation was flown on a motion base it was discovered that the 'slapdown' immediately after ground contact was more severe than expected, because the elevons sometimes went to their upper limits after touchdown. Moving the main landing gear forward to reduce the main gear pitch moment arm solved the problem. This project also investigated the limits for crabbed crosswind landings, since it is tricky to decrab a lifting body landing deadstick at 210 knots. The gear model provided preliminary estimates of the required strength of the landing gear and control authority during landing and rollout.

The ‘tricycle approximation’ was first tested with the Rollout and Turnoff (ROTO) project modeling a Boeing 737 in FORTRAN in 1997. One of the objectives of this project was to simulate high-speed turnoffs requiring high gains on the motion base. The discontinuities in the landing gear model at low speed became very pronounced on the motion base. The tricycle approximation was used at low speeds to alleviate these discontinuities and still produce realistic results.

The LaSRS++ General Aviation Baseline project is designed to easily simulate different aircraft by changing only a few program parameters, including aerodynamics, propulsion, and landing gear. The Generic Gear Model was used for this simulation since no landing gear model was specified and the model already provides the needed flexibility. The same object-oriented class used for the HL-20 is the base class for the General Aviation Baseline gear class. Its constructor function provides default values applicable to the aircraft being simulated. Values can be changed in real-time via a graphical user interface (GUI). This project has been simulating a Cessna 172 aircraft, including takeoff, landing, and taxiing, since October 1999 in a fixed-base cockpit.

The LaSRS++ generic fighter simulation models an aircraft similar to an F-16 and is used as a test bed for the LaSRS++ framework. It includes the Generic Gear Model and demonstrates the ability to model ground dynamics for such aircraft by changing only the gear model inertia and geometry parameters. This provided more confidence in the typical dynamics parameters that are assumed to be the same for all aircraft.

Figures 5(a) and 5(b) show the results of an HL-20 landing using the Generic Gear Model. The run begins with the aircraft 5 feet above the ground with a sink rate about 4 feet/sec. The following control inputs were made:

- At 5 seconds 50% braking is applied.
- At 15 seconds differential braking, 60% left and 40% right, is applied
- At 20 seconds brakes are released
- At 25 seconds 50% right rudder pedal is applied, deflecting the nose wheel 7.5 degrees
- At 30 seconds the pedals are centered
- At 35 seconds 50% left rudder pedal is applied
- At 40 seconds the pedals are centered and 25% brakes are applied until the aircraft stopped at around 45 seconds

These plots were generated by a batch test, using step inputs that are more abrupt than with a pilot in the loop. The damping and frequency of the dynamics are evident.

Conclusions

The LaSRS++ Generic Gear Model has demonstrated a simple and flexible model that can be used to simulate ground dynamics for a variety of aircraft, including general aviation, fighters, and lifting bodies. The Generic Gear Model is presently being used in a simulation of general aviation, the HL-20 lifting body, and a generic fighter similar to an F-16. There are also plans to use the Generic Gear Model in a future civil transport simulation. The results are not notably different from those produced by more complex models, and in some cases are more realistic, especially at low speeds.

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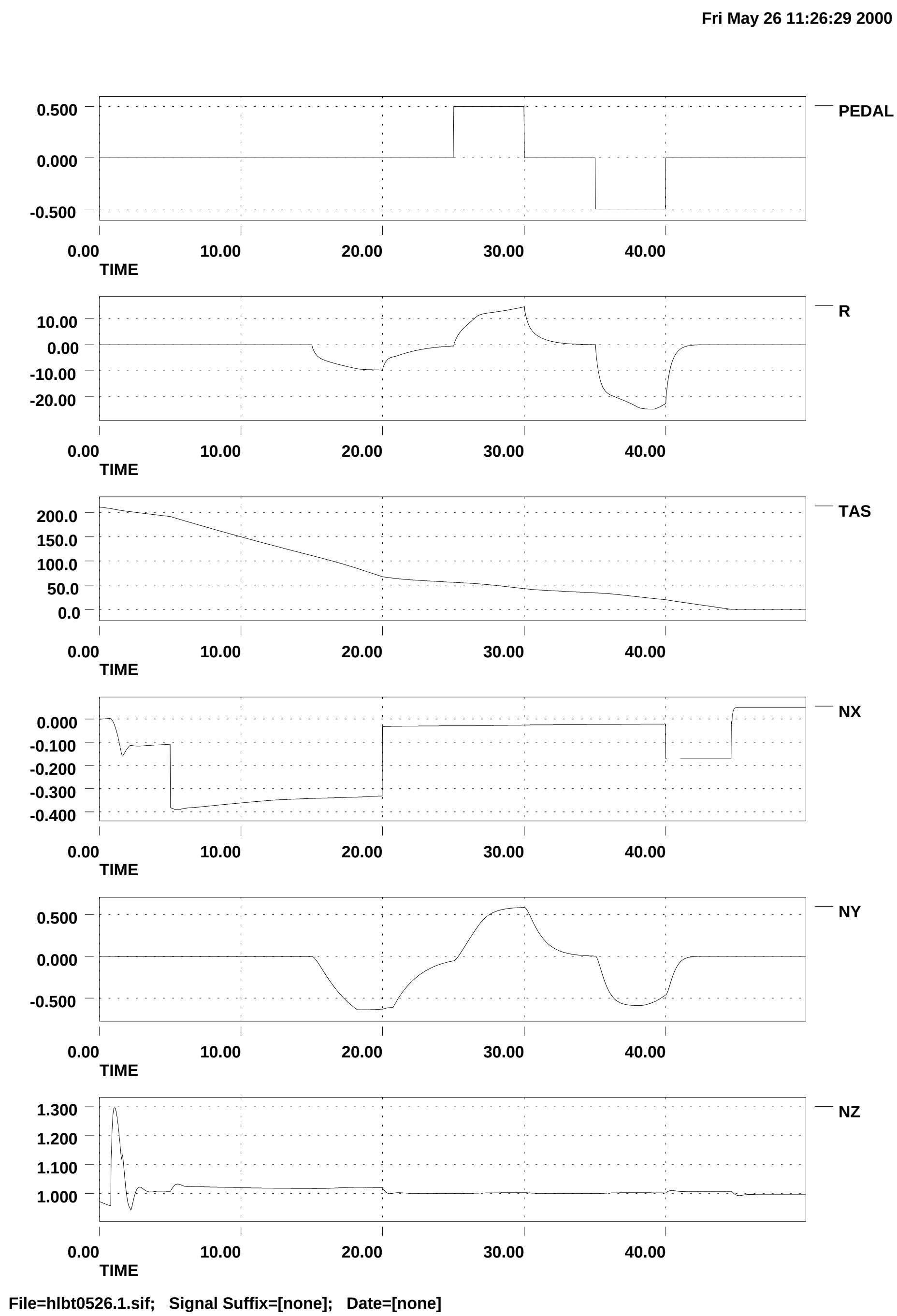

t=5 sec 50% brakes, t=15 sec 60/40% brakes, t=20 sec zero brakes, t=25 sec 50% pedal, t=30 sec zero pedal, t=35 sec -50% pedal, t=40 sec zero pedal & 25% brakes, t=45 stop

Figure 5(a). HL-20 Landing Dynamics Using the Generic Gear Model

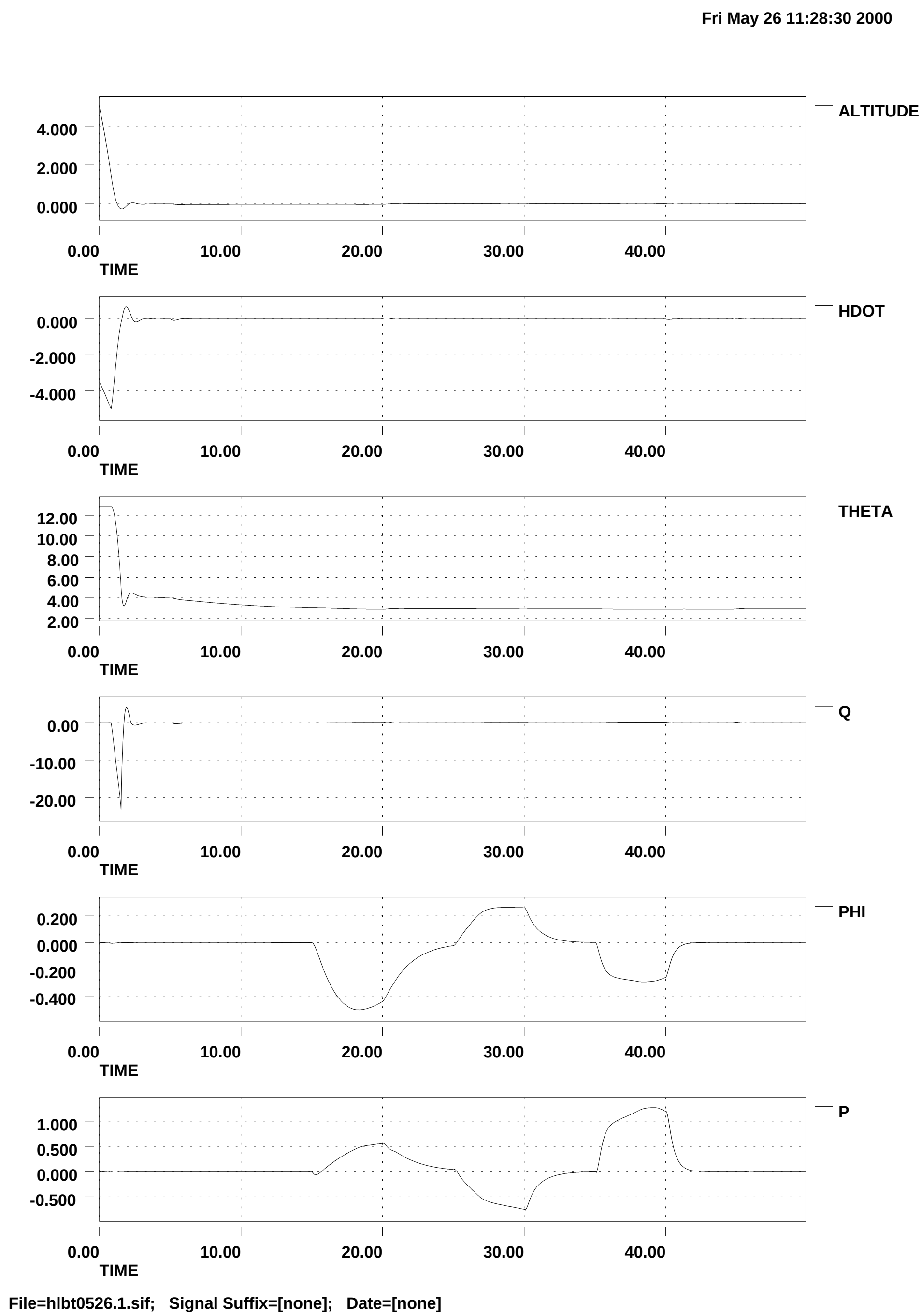

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Figure 5(b). HL-20 Landing Dynamics Using the Generic Gear Model